Technical Report Documentation Page

1. REPORT No.

2. GOVERNMENT ACCESSION No.

3. RECIPIENT'S CATALOG No.

4. TITLE AND SUBTITLE

Some Concepts Concerning Triaxial Compression Testing of Asphaltic Paving Mixtures and Subgrade Materials

5. REPORT DATE

October 1949

6. PERFORMING ORGANIZATION

7. AUTHOR(S)

Hveem, F.N. and Harmer E. Davis

8. PERFORMING ORGANIZATION REPORT No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

10. WORK UNIT No.

11. CONTRACT OR GRANT No.

12. SPONSORING AGENCY NAME AND ADDRESS

13. TYPE OF REPORT & PERIOD COVERED

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Authorized reprint form the copyrighted Triaxial Testing of Soils and Bituminous Materials Special Publication No. 106 Published by the American Society for Testing Materials Philadelphia, Pa. 1951

16. ABSTRACT

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During the past two decades, independent but almost parallel lines of thought have developed among those who have been concerned with soils and among those who have been concerned with bituminous mixtures. In keeping with the symposium idea, wherein each participant contributes by presenting his views or experiences on the central theme, an attempt is made to summarize in this paper some of the thoughts, doubts, and developments which have come out of the exchange of ideas and cooperative efforts of a small group of men on the West Coast who have been debating the problems of stability of bituminous mixtures.

17. KEYWORDS

18. No. OF PAGES:

24

19. DRI WEBSITE LINK

http://www.dot.ca.gov/hq/research/researchreports/1930-1955/50-02.pdf

20. FILE NAME

50-02.pdf

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Triaxial Testing of Soils and Bituminous Materials
Special Publication No. 106
Published by the
AMERICAN SOCIETY FOR TESTING MATERIALS
Philadelphia, Pa.
1951

SOME CONCEPTS CONCERNING TRIAXIAL COMPRESSION TESTING OF ASPHALTIC PAVING MIXTURES AND SUBGRADE MATERIALS*

BY F. N. HVEEM[1] AND HARMER E. DAVIS[2]

Clear-cut concepts readily applicable to the everyday problems of structures composed of granular materials have been relatively slow to develop, in comparison with knowledge of the mechanics for the more homogeneous materials of construction. This is due in part to lack of suitable experimental techniques by which to explore and evaluate such theory as has been evolved. In recent years, an accelerated groping for means of controlling the behavior of granular mixtures has led to a vast amount of experimentation and the accumulation of much uncoordinated data. In a sense, this accumulation of information has outstripped the capacity of existing theory to explain. It seems most timely, then, that attempt should be made to take stock of theoretical concepts, experimental procedures, and performance records and to assess their significance as a basis for further development.

During the past two decades, independent but almost parallel lines of thought have developed among those who have been concerned with soils and among those who have been concerned with bituminous mixtures. In keeping with the symposium idea, wherein each participant contributes by presenting his views or experiences on the central theme, an attempt is made to summarize in this paper some of the thoughts, doubts, and developments which have come out of the exchange of ideas and cooperative efforts of a small group of men on the West Coast who have been debating the problems of stability of bituminous mixtures.

FORMATION OF THE TRIAXIAL INSTITUTE

Since some of the individuals involved had been experimenting with triaxial compression test methods for road building materials with considerable success for a period of years, attention was readily focused on an examination of the triaxial principle. The group was organized under the somewhat imposing title, the "Triaxial Institute," and the name has been applied to the group, at least locally, since its organization.

The motivation for this group and the reasons for its creation were expressed in the opening paragraphs of the initial letter written by C. V. Kiefer[3] in 1947:

"In order to develop, standardize and promote the principles of triaxial testing, the Pacific Coast Division (DIV. V) of the Asphalt Institute has decided to instigate the formation of a Triaxial Institute—Western Division. Accordingly, the writer was appointed temporary chairman to undertake the organization of such a group.

"Recognizing the great universal need for

* A combination and revision of a paper presented by Mr. Hveem at the Session on Bituminous Paving Mixtures held at the First Pacific Area National Meeting of the Society, San Francisco, Calif., October 10, 1949; and a paper presented by Messrs. Davis and Hveem at the Fifty-third Annual Meeting of the Society, Atlantic City, N. J., June 28, 1950.

[1] Construction Engineer, Headquarters Office, California State Division of Highways, Sacramento, Calif.; at time of presentation of paper, Mr. Hveem was Supervising Materials and Research Engineer in the Materials and Research Laboratory.

[2] Director, Institute of Transportation and Traffic Engineering, University of California, Berkeley, Calif.

[3] Shell Oil Company, San Francisco, Calif.

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a standardized method of evaluating the load-supporting characteristics of soils, bases, and flexible pavements and believing that the underlying principles embodied in the triaxial method are sound, it is hoped that by the formation of such a group, a unified approach to the problem may be evolved.

"Presently, several separate organizations utilize triaxial testing in one form or another but no two are exactly parallel in all respects. If standardized procedure, units of measure, and nomenclature can be secured by cooperative tests, discussions and the evaluation and comparison of data, a great service will have been rendered flexible pavement design. Such, in brief, will be the purpose of the organization."

A small group was organized consisting of the following members:

Education and Research Interest:
R. G. Hennes, University of Washington
H. E. Davis, University of California
State Highway Interest:
Bailey Tremper, State of Washington
N. M. Finkbiner, State of Oregon
F. N. Hveem, State of California
Asphalt Interest:
Vaughn Smith, California Research Corporation
V. A. Endersby, Shell Development Co. (*Chairman*)

The initial meeting was held in Klamath Falls, Ore., in May, 1948. Much detailed discussion was carried on and the following review of the background by Chairman Endersby expresses the general viewpoint at that time:

"The group has been formed in an attempt to ameliorate the current confusion in the asphalt field in regard to methods of testing the mechanical stability of road materials. At the present time a number of methods exist among triaxial tests, such as the Hveem stabilometer and the Asphalt Institute methods; among other types, the Hubbard-Field, the Marshall, various shear tests, and bearing tests such as California Bearing Power. The use of most of these has been based upon empirical correlations with road work; to date it is difficult to coordinate basic conceptions of users or results of different methods, and especially difficult to render results in commonly accepted engineering units, in such manner that the results of tests can be interpreted scientifically as well as practically. In addition, there is a continuing development of new tests, likewise empirically based, which tends to confuse the field still more. It is thought that the composition of the present group is well adapted to scientific analysis of tests . . . as well as fitted to work out methods practically usable by engineers in the field. The members agreed that triaxial methods were the most promising."

The scope and aims of the Triaxial Institute and certain objectives were agreed upon as follows:

1. Clarification of the fundamental mechanics of granular particles combined with viscous binders (including water).
2. Investigation of the triaxial compression test as means for measuring certain pertinent mechanical properties.
3. Consideration of specific procedures for conducting the triaxial test.
4. Preparation of a report (to the Asphalt Institute) covering specific application to bituminous mixtures.

THE TRIAXIAL INSTITUTE AND THE ASTM

Because of the affiliation of a number of its members with the ASTM, and because of the possibility that test methods of widespread interest might be evolved, the group was later made a project committee of Subcommittee B-2, ASTM Committee D-4 on Road and Paving Materials. At San Francisco in October, 1949, the group met as an ASTM project committee.

It was recognized that the membership of the group as originally constituted naturally represented different viewpoints and to a degree, at least, could be recognized as having somewhat different motivations. For example, quoting from the minutes:

"State and educational members were much interested in applications to soil mechanics; but inasmuch as soils were mechanically similar to bituminous mixes, basic principles of the latter would apply to the former. Also the composition of bituminous mixes was more easily controllable than that of soils, thus presenting easier base materials for investigation of fundamentals. Thus, it was agreed that investigation would not be made on soils at least until tangible conclusions were arrived at on bituminous materials, after which the position would be reviewed. Attention was also called to the fact that while the group as the "Triaxial Institute" has autonomy and wide discretion in its work, as an ASTM committee its scope is limited to bituminous materials, soils investigations in ASTM being under Committee D-18."

ATTENTION DIRECTED TO TRIAXIAL TESTING

Evidence available, together with theoretical considerations, seemed to support the decision to concentrate attention upon the triaxial type of test. There was general agreement from a consideration of the fundamental factors underlying the stability problem that the results of tests from any apparatus for testing bituminous paving specimens which included tensile strength or cohesive forces to an *indeterminable* degree would be likely to give poor correlation with performance. This means, for example, that unconfined compression tests *in any form* are likely to give undependable or misleading information.

Attention of the group was early directed to the specific questions concerning the type and dimensions of triaxial apparatus. Most members of the committee had carried on actual testing work with some form of apparatus utilizing the triaxial principle. Smith, of the California Research Corp., had spent considerable time in investigation and development, and in 1944 had published articles[4] describing his form of the triaxial test which was later accepted as a procedure of the Asphalt Institute. Smith had adopted a 4-in. diameter by 8-in. high test specimen. After a study of available literature, which generally favored a triaxial test specimen having a height-diameter ratio of 2.0 or more, the "tall" specimen of 4-in. diameter had been adopted on theoretical grounds from general scientific considerations to avoid end effects and disturbances due to irregularities in large-particle content.

Hveem had been using the Stabilometer[5] since 1931, the Stabilometer being a form of the triaxial apparatus which utilized a 4-in. diameter by 2.4-in. high specimen, giving a low height-diameter ratio of 0.6. This apparatus was developed primarily to satisfy practical considerations, and the original purpose was to develop an instrument that could be used for routine testing in a large highway laboratory. Theoretical considerations were largely subordinated to such requirements as rapid testing schedules and the need for rugged, durable equipment that could be easily maintained in adjustment; the height of the specimen was selected to correspond to the typical thickness of bituminous surfacing commonly used in highway work; economy of material and fabrication cost were also considerations.

Many arguments and viewpoints were set forth, as stated by Endersby:

"It was found that a difference, though not a conflict, of interest existed among the organizations present. All alike were concerned with improving tests so that better roads could be built more cheaply; educational interests were for uniformity of tests and conceptions on

[4] V. Smith, "A Method for Preparing Soil and Aggregate Specimens of Homogeneous Density and Composition," *Journal of Asphalt Technology*, Vol. 3, No. 1, January, 1944.
V. Smith, "Flexible Pavement Foundation Design," *Journal of Asphalt Technology*, Vol. 3, No. 1, January, 1944.

[5] See Appendix II for description of the stabilometer and the procedure related to its use, p. 36.

general principles, but the oil companies were particularly interested in standardization because of the large number of users of asphalt from different types of organizations. Uniform standards and specifications, and uniform and correct methods of determining the true responsibility for road failures were directly to their interest."

CONSIDERATION OF MATERIALS AND FUNDAMENTAL PROPERTIES

Some time was spent in a discussion of the nature, properties, and characteristics of asphaltic paving mixtures, consisting of fragmental stone particles ranging in size from fine sand or dust to coarse aggregate—all cemented by a viscous liquid. A typical bituminous paving mixture consists of 90 to 95 per cent of rock particles coated and cemented together by a quantity of asphalt ranging normally from 5 to 10 per cent by weight. A detailed discussion developed around the parts played by the two ingredients which compose a bituminous pavement. Recognition of the predominant influence of the aggregate led to a discussion of the properties associated with such materials, especially those properties associated with surface characteristics.

Among the properties influenced by surface characteristics, inter-particle friction is the most important so far as stability is concerned. Quoting from the minutes, "Friction could be defined generically as the resistance to the dragging of one surface over another. One characteristic of this friction is that the sliding resistance is proportional to the load normal to the sliding plane. This, which is the classic view of friction found in text books, was properly called 'Coulomb friction' after the discoverer of the law." In a later discussion, Hveem pointed out that the original discovery may more properly be credited to Amontons, who formulated the law in 1699. Amontons' law states that friction between solid bodies is affected by the pressure but is independent of the speed and of the area in apparent contact. Coulomb later (1781) confirmed this law.

Discussions of friction and the general problem of stability brought forth, from time to time, views concerning the use of the Mohr diagram. No implication was made that the use of the Mohr diagram was fundamentally unsound, but it was pointed out that the Mohr circle is merely the graphic representation of the state of stress at a point and that further superposition of failure lines rest on concepts of modes of failure. It was pointed out by Hennes that the assumptions (for example, Coulomb criterion of failure) underlying the application of the Mohr diagram indicate that the Mohr envelope should be a straight line, whereas a curved envelope is frequently developed when experimental data from a triaxial test is plotted. Thus, drawing the usual tangent line may represent a generalization (or simplification) that masks the factors which are of significance in attempting to arrive at valid conclusions covering pavement stability.

Quoting from the minutes, it was further pointed out by Hennes "that while the Mohr envelope projected to the negative side of the origin gives a true tensile strength in metals, the physical properties of asphaltic mixes are very different and do not seem to lend themselves to a rigorous Mohr interpretation."

These critical questions concerning the use of the Mohr diagram appear to be timely and pertinent. W. S. Housel has even more strongly challenged the applicability of the Mohr concept in this particular field.[6]

Questions concerning the use of the Mohr diagram were not resolved, but it was recognized that, with masses of stone particles in contact, part of the resistance commonly designated as "friction" usu-

[6] W. S. Housel, "Interpretation of Triaxial Compression Tests on Granular Mixtures," p. 267 this publication.

ally includes factors described by some as "interlock" and by others as "arch action," which factors, regardless of terminology, are resistances to sliding not dependent upon cohesion and perhaps not subject to "Coulomb's law."

Discussion also embraced the nature of "cohesion." It was recognized, of course, that the term "cohesion" as commonly used in the literature on soil mechanics does not correspond to the ordinary or dictionary meaning, as it appears that the term cohesion commonly applied to soils test data means only that portion of the resistance to shearing that is independent of the pressure, while the dictionary meaning implies that cohesion is the resistance to pulling apart, that is, a tensile resistance. This discussion led to consideration of the real meaning of the Mohr intercept which is usually regarded as a measure of sliding cohesion. It was concluded that until more evidence could be made available, the intercept value of the Mohr diagram should be designated simply as "the Mohr intercept" without any *a priori* assumption as to its true significance.

It was pointed out that the phenomenon of cohesion was nonexistent in an aggregate mass intended for a bituminous mixture until the asphalt has been introduced and, therefore, in this case any cohesive or tensile strength is due to and characteristic of the particular viscous liquid under the particular conditions of temperature, rate of strain, etc. Sir W. B. Hardy[7] had pointed out that "viscosity" is the common term for "the simple internal friction of a liquid." Any resistance to movement caused by this internal fluid friction is increased by the speed of action and by the area of surfaces in contact This law is in marked and interesting contrast to Amontons' law.

[7] Jerome Alexander, "Friction, Surface Energy and Lubrication," *Colloid Chemistry*, pp. 288–305.

PROBLEM OF PREPARING REALISTIC TEST SPECIMENS

Regardless of the stability testing device to be utilized, it was evident that the matter of forming (that is, "compacting") the specimens to be tested was a matter of prime practical importance. As stated by the minutes of the May 1948 meeting:

"The Division of Highways of the State of California has used a kneading method for many years, modified from time to time by experience and comparison with road samples. California Research Corp. uses similar methods, and the Martinez Laboratory of the Shell Oil Co. has just been equipped with such a machine.

"In these machines a tamping shoe having the form of a segment of a circle applies load by a reciprocating motion to the sample, which is gradually built up under it. The sample mold rotates as the shoe rises and falls. The feed is automatic. The load is constant and is applied as a pressure, not a blow.

"Hveem stated that in his experience this method also is capable of producing an amount of degradation of the material comparable with that which occurs in a pavement.

"At this point the discussion turned for a time on the problem of degradation and its effect on road performance. According to the experience at Shell Development Co., degradation must be considerable, especially in angular aggregates, since a sample only retested once showed markedly less internal friction and interlock than in the first test. Some members expressed doubt that the Los Angeles rattler test really correlated with road experience in asphaltic mixtures. It was noted that some systematic studies on degradation were beginning to appear in the literature.

"The committee unanimously agreed that kneading compaction methods were necessary to useful investigation; otherwise there could be no certainty that the samples tested in the laboratory would correlate in mechanical properties with those placed in the field. Smith suggested that compaction method giving lowest stability for the same density would correlate best with field practice."

Hveem, Smith, and Davis "were designated as a special committee to recommend a standard tamping shoe and the exact movement of same." Load was also to be specified, but the machine was to be built in such a manner that it could quickly be changed for purposes of investigation. The critical points were the extent of lift of the shoe, its dimensions, and shape, the overlap of successive application areas, its speed and "dwelling time" on the sample, increments of feed, applications per unit height of sample, and type of mold and mold lining (rubber or metal), temperature of mix and shoe, and final smoothing pressure.

Following the preparation of a working drawing by the California State Highway Laboratory, agreements were reached concerning controlling features of the compactor at a meeting of the group in Portland, Ore. in October, 1948. After the operation of the pilot model (Model A) constructed at the University of California was studied, certain minor modifications were indicated and a second machine (Model B) embodying these revisions was built in the laboratory of the California Division of Highways.

In the summer of 1950, the California Division of Highways began arrangements for the manufacture of eight compactors (Model C), embodying still further improvements. By the end of the year 1950 at least 16 compactors of this design will have been placed in operation: 10 by the California Division of Highways, 2 at the University of California in Berkeley, one each with the State Highway Laboratory in Washington and in Colorado, one by the County of Los Angeles, and one by the Wood River Refinery of the Shell Oil Co. in Illinois.

At the San Francisco meeting of October 1949 referred to earlier, a report was made by B. A. Vallerga of the University of California, showing pressure application curves, recorded by special electronic gaging equipment, for the first compactor built by the University. A typical curve, shown in Fig. 1, illustrates the interval between load applications, the rate at which pressure increases, and the length of time, or "dwell," of the compactor foot on the specimen during forming. Subsequently, compaction pressure studies were made by Vallerga on the machines in use in the laboratories of the participating members of the group in California.

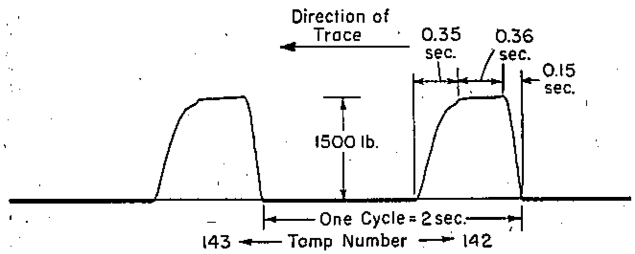


FIG. 1.—Time Pressure Curves for Kneading Compactor.
University of California
Test Run IV September 28, 1949
Air Pressure = 60 psi.
Feed Valve Open 1¼ Turns

Consideration of further details of testing procedure led to the study and adoption of a standard laboratory mixer. Mixers of the approved design were placed in use by the California Highway Laboratory, by the University of California, and by the Washington State Highway Laboratory. Working drawings were made available to interested agencies.

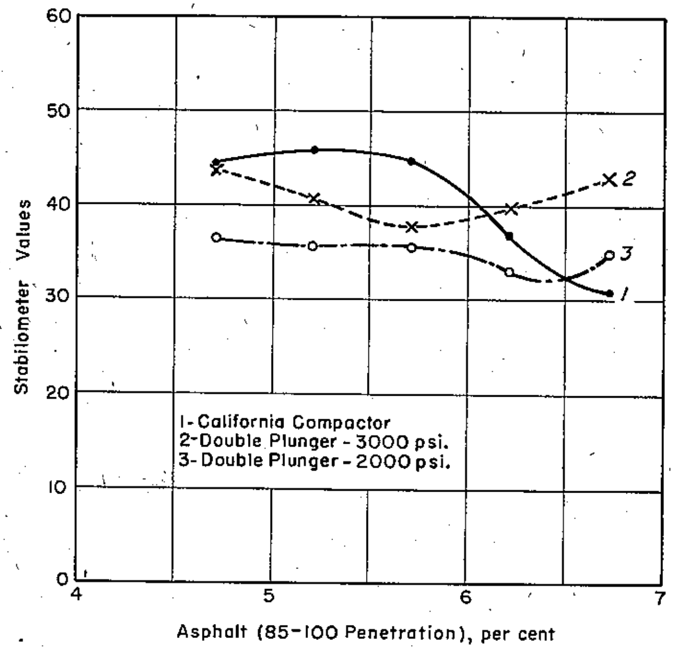


FIG. 2.—Material "A" Crushed Gravel (Mixed Composition).

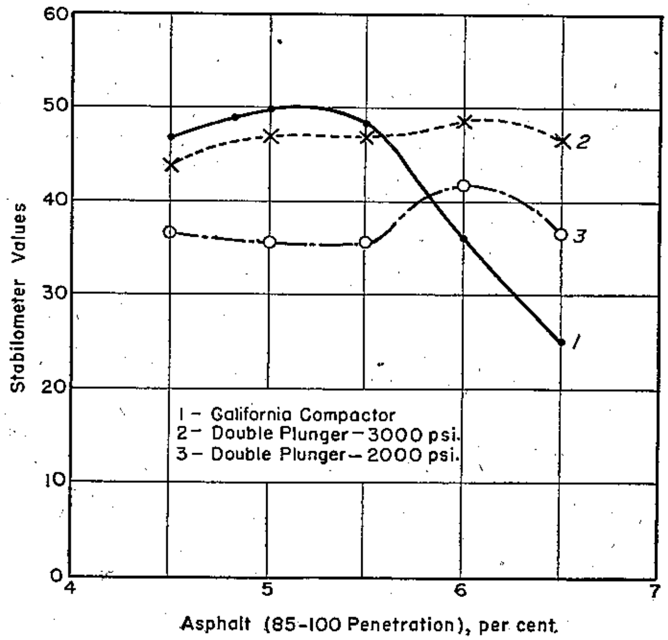


FIG. 3.—Material "B" Crushed Granite.

It was also agreed, that mixing temperatures for preparation of bituminous mixes in the laboratory should be such as to reduce the viscosity of the asphalt to a range from 75 to 150 sec. Saybolt Furol, and that after mixing, the curing time of liquid asphalts should be a period of 16 hr. at 140 F. with provision for air circulation. This period of artificial curing appeared to be reasonable when compared to conditions on the road after placing.

Methods of feeding the material into the forming mold during the compaction period were also considered at the San Francisco meeting. However, experience since the meeting does not indicate that this is a serious problem and several types of feeders might be used. The compactors so far constructed are equipped with belt-type feeders, but the California Division of Highways proposes to use simple hand-operated devices for the machines in use in the District laboratories.

In summary, as a result of the first year of activity of the Triaxial Institute, an agreement was reached and action instituted which has led to the adoption of a standard mechanical apparatus and procedure suitable for compacting test specimens of either bituminous mixtures, crusher run or gravel bases, subbases and subgrade soils; also methods of mixing and for curing were agreed upon.

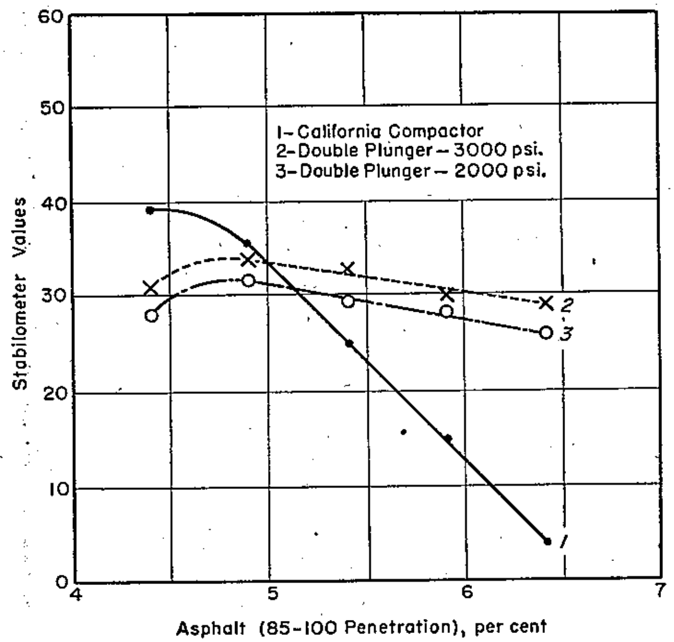


FIG. 4.—Material "C" Quartz Gravel.

COMPARATIVE TESTING PROGRAM

At the meeting of the group in Portland, Ore. in October, 1948, consideration was given to a study program which would involve cooperative testing. This program was further developed and at the present time tests, involving over 500 specimens, are under way by several of the cooperating agencies. Principal variables in the study program are: method of compaction and type of triaxial test specimen.

It was pointed out by Tremper that mixes containing certain aggregates are particularly sensitive to the effects of compaction and to asphalt content; hence it was agreed that several types of aggregates should be included in the cooperative program. One of the aggregates selected was a crushed granite, a large quantity of which was secured, separated into sizes and distributed to those members who were equipped to perform tests. At the present writing, comparative results from all laboratories are not available. However, preliminary tests in the California Highway Laboratory indicate the marked difference in evaluation which can result depending upon the type of compaction utilized. Figures 2, 3, and 4 illustrate the variations in stability mixtures as measured by the stabilometer made with three different aggregates of the same gradation and having identical mixture compositions, compacted by the mechanical kneading compactor.

A few preliminary tests have also been carried out by the laboratory of the University of California, comparing the Asphalt Institute Triaxial Method as developed by Smith of the California Research Corp. with similar mixtures tested in the Hveem Stabilometer. This work is by no means final, but the results indicate a linear relationship between the two tests. Figure 5 shows the results obtained by plotting the lateral pressures developed by tall specimens of the same mix tested in the stabilometer. There are certain dissimilarities of testing procedure involved; for example, corrections are commonly made for variations in the volumetric displacement in the stabilometer. These corrections have not been applied in the Asphalt Institute triaxial device, and a more detailed study of the data may indicate a closer correlation than is apparent in the plot shown in Fig. 5.

COMMENTS CONCERNING INTERPRETATION OF STABILITY DATA

At present, there is no reason to believe that a given series of materials ranging from low to high stability will suffer any marked difference in relative classification whether tested in the Stabilometer or in the triaxial device using tall specimens. The advantages for speed of testing and simplicity of operation are in favor of the methods employed with the Stabilometer. On the other hand, the use of the triaxial test with means for carefully controlling and measuring a number of variables may continue to be more attractive to those interested in

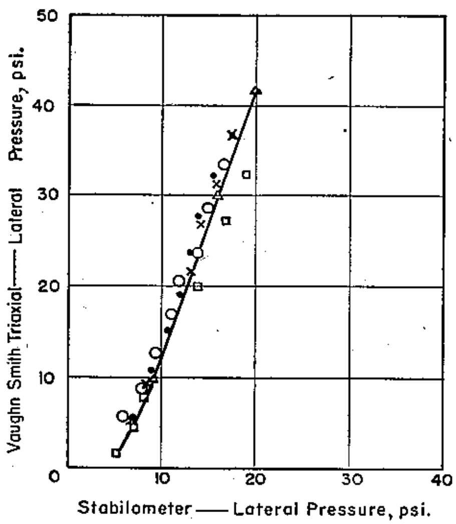


FIG. 5.—Lateral Pressures Developed on Bituminous Paving Mixtures. Smith Triaxial Device Compared to Hveem Stabilometer. Points plotted at same vertical pressures.

theoretical studies and in investigation of basic principles.

Whether or not test data derived from the Stabilometer test are susceptible to mathematical treatment and translation into the usual concepts of angle of friction and "cohesion" requires further study. It may be pointed out that L. E. McCarty of Texas published two articles[8, 9] indicating that these commonly

[8] L. E. McCarty, "Applications of Mohr Circle and Stress Triangle Diagrams to Test Data Taken with the Hveem Stabilometer," *Proceedings*, Highway Research Board, Vol. 26, pp. 11–123 (1946).

[9] L. E. McCarty, "Further Methods for the Analysis of Data Taken in the Hveem Stability Test," *Proceedings*, Highway Research Board, Vol. 27, pp. 455–466 (1947).

used factors may be derived from tests on a short specimen as readily as from the more involved triaxial method. Mr. R. M. Carmany has submitted a formula and derivation for computing friction and cohesion from Stabilometer test data (see Appendix I). However, the question of the calculation of ϕ and C from any triaxial test is something apart from the question of whether ϕ and C are concepts by which it is most desirable to interpret the stability of mixtures for pavement structures. It is not immediately apparent that any large degree of practical benefit is derived from such calculations. Much structural design data used in other branches of engineering rests upon the evaluation of materials in terms of simple compressive strength, as in the case of concrete, or upon simple tensile strength, as in the case of reinforcing steel. There is some justification for the notion that fragmental masses such as soils, gravel bases, and bituminous pavements may be better classified in terms of their ability to resist deformation. Further, because roughness and corrugation of flexible pavements may develop before "failure" (in the sense of complete rupture) has occurred, there appears to be considerable justification for expressing resistance in the working range, regardless of forces required to produce ultimate disruption. This concept is being adopted by the California Division of Highways at the present time. The new design procedure expresses the ability of the underlying soils and base materials to sustain loads in terms of the resistance value R which is derived directly from Stabilometer tests on the "short" specimens which are subjected to relatively light loads of 160 psi.[10]

[10] F. N. Hveem, and R. M. Carmany, "The Factors Underlying the Rational Design of Pavements," *Proceedings*, Highway Research Board, Vol. 28, pp. 101-136 (1948).

CONCLUSION

At the present time, therefore, the trend of thinking and work conducted by the Triaxial Institute indicates that for day-by-day routine testing in highway laboratories where the volume of work is very large and the need for rapid testing becomes acute, the Stabilometer method seems to promise the greatest over-all speed of operation, which means that a larger number of individual tests can be performed. This is an important item when dealing with materials from sources that are inherently non-uniform and variable. The triaxial device using tall specimens, either with the open or closed system, where loads are applied slowly and allowed to come to an equilibrium, will no doubt continue to have a place, especially for instruction work in university and other research laboratories, and also may prove to be especially suitable for developing data for the analysis of slope stability pressures on retaining walls, etc. Only time and continued work will settle these questions to the satisfaction of all concerned.

In the meantime, it is felt that something has been accomplished in recognizing the need for careful and controlled preparation of test specimens. With a workable procedure agreed upon for the testing and evaluation of bituminous pavement mixtures and combinations, it will be a logical step to extend these procedures and principles to the testing of the supporting base and foundation soils upon which all bituminous pavements must depend for support. The triaxial principle has the special advantage that all layers composing structure and substructure underlying a bituminous pavement may be tested and evaluated in the same frame of reference so far as plastic deformation is concerned.

APPENDIX I

THE DERIVATION OF THE FORMULA FOR COMPUTING FRICTION AND COHESION FROM STABILOMETER TESTS EMPLOYING SPECIMENS HAVING A LOW HEIGHT-DIAMETER RATIO

PREPARED BY R. M. CARMANY, CALIFORNIA DIVISION OF HIGHWAYS

This method of determining the cohesion and angle of friction is based upon the assumption that when the h/d ratio of the specimen is such that the specimen cannot fail along a plane making an angle $\alpha = 45 + \frac{\phi}{2}$ with the horizontal due to the interference of the testing machine platen, it is forced to fail along a plane making an angle $\alpha = \tan^{-1} h/d$ with the horizontal; that is, from corner to corner of the specimen.

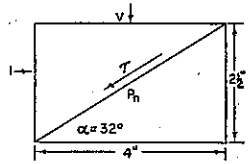
α = angle between the plane of failure and horizontal,

P_n = normal pressure on the plane of failure,

τ = shearing stress on the plane of failure,

v = vertical pressure,

l = lateral pressure.



$$P_n = \frac{v+1}{2} + \frac{v-1}{2}\cos 2\alpha \qquad (1)$$

$$\tau = \tfrac{1}{2}(v-1)\sin 2\alpha \qquad (2)$$

At conditions of test

$$\tau = C + P_n \tan\phi \qquad (3)$$

where:

C = cohesion, and

ϕ = angle of friction.

Substituting Eqs. 1 and 2 into Eq. 3

$$\tfrac{1}{2}(v-1)\sin 2\alpha = C + \left(\frac{v+1}{2} + \frac{v-1}{2}\cos 2\alpha\right)\tan\phi \qquad (4)$$

Substituting values for two conditions into Eq. 4

$$\tfrac{1}{2}(v_1 - l_1)\sin 2\alpha = C + \left(\frac{v_1 + l_1}{2} + \frac{v_1 - l_1}{2}\cos 2\alpha\right)\tan\phi \qquad (5)$$

$$\tfrac{1}{2}(v_2 - l_2)\sin 2\alpha = C + \left(\frac{v_2 + l_2}{2} + \frac{v_2 - l_2}{2}\cos 2\alpha\right)\tan\phi \qquad (6)$$

and solving for C and $\tan\phi$

$$C = \frac{0.45(D_2S_1 - D_1S_2)}{0.44(D_1 - D_2) + S_1 - S_2}$$

where:

$D_1 = v_1 - l_1$

$D_2 = v_2 - l_2$

$S_1 = v_1 + l_1$

$S_2 = v_2 + l_2$

$$\tan\phi = \frac{0.9(D_1 - D_2)}{0.44(D_1 - D_2) + S_1 - S_2}$$

APPENDIX II

THE HVEEM STABILOMETER METHOD

The following is a condensation of the paper presented to the First Pacific Area National Meeting of the American Society for Testing Materials held in San Francisco, Calif., October 10 to 14, 1949.

The details of performing tests by the use of triaxial apparatus utilizing tall specimens have been fully reported and described elsewhere. However, there has been no similar publication covering the details of Stabilometer operation and interpretation of test results. The following brief description is, therefore, confined only to the Stabilometer using specimens having a low height-diameter ratio.

Definition:

The name "Stabilometer" is a coined word and was intended to apply only to the type of apparatus described herein. The term is not properly applied to other devices of different principle that have been proposed for measuring "stability."

Development:

The Stabilometer has been employed as a routine test in the laboratory of the Materials and Research Department, California Division of Highways, since 1930, the first models being simple metal cylinders split on one side and held together by compression springs which permitted expansion of the cylinders when subjected to internal pressures. In 1932, the design was changed to the present hydraulic type in which lateral pressure is transmitted through the walls of a rubber tube to an annular liquid cell. Lateral pressure is measured by means of a standard hydraulic pressure gage (Fig. 6).

The Stabilometer was originally developed because of the pressing need for a means to evaluate the stability of the oil mix type of bituminous surfacing which was then a relatively new process, the first oil mix road surface in California having been constructed in 1926.

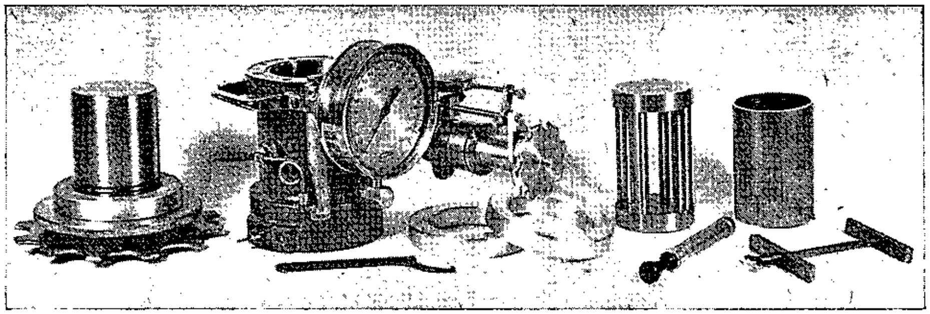


FIG. 6.—Complete Stabilometer Assembly.

At extreme left, base column with adjustable stage.
Second, the main unit containing the liquid cell and gages.
Right of Center, aluminum bushing rings for use with tall specimen.
Cage type piston or follower for applying load to the test specimen.
On the right, brass cylinder 4 in. outside diameter for use as dummy specimen.
Miscellaneous items include spanner wrench for tightening pump gland, small air pump for adjusting initial displacement and clamp tool for installing new rubber diaphragm.
(The Stabilometer illustrated is complete except for crank handle attachment on displacement pump.)

Attempts to apply stability tests such as the Hubbard-Field, miscellaneous shear tests or unconfined compression tests to specimens of the oil mix types gave values that were extremely low compared to standards thought necessary to assure stability in pavements of the sheet asphalt type. It was evident that in spite of the low values registered by many of the so-called stability tests, dense graded mixtures using slow curing liquid asphalts similar to the present SC-2 grade (having a viscosity range from 100 to 200 sec. at 140 F.) were capable of withstanding considerable amounts of traffic and the conclusion was inescapable that such satisfactory road surfaces must therefore possess the requisite "stability."

Examinations of failures on the road caused by instability of a bituminous surfacing indicate that the paving mixture tends to flow in a lateral direction giving the appearance of being squeezed out or "rolled" out beneath the wheels of heavy vehicles. It, therefore, seemed to be a fairly obvious and simple conclusion that the ability to resist lateral displacement is a characteristic of *stable* bituminous pavements. In view of the fact that all pavements represent very large areas compared to the area covered by a single vehicle tire, it is also evident that in order for the material beneath the tire to flow or "escape" in a lateral direction it must transmit pressures greater than the resistance of the surrounding mass of similar composition. By way of illustration; if a hole with a diameter corresponding to a tire print is bored in solid material such as concrete and filled with either clean sand or plastic clay, these materials will sustain a load covering the area of the hole simply through the influence of lateral support alone. Conversely, an isolated block of concrete or of stone would sustain any load which could be transmitted by a pneumatic tire simply because of the internal resistance or strength of the unit directly beneath the load. Therefore, assuming an adequate foundation, the capacity of a bituminous pavement to remain smooth and undistorted under traffic depends upon the ability of the pavement mass to *resist* plastic deformation.

Perhaps the properties of plastic materials may be better visualized by extending the principles of hydrostatics rather than by an attempt to analyze behavior through applying the theory of elasticity. If the mechanics of bituminous pavements or of granular soil materials is compared to the behavior of liquids under pressure, it will be recognized that one of the characteristics of liquids is the ability to transmit pressure equally in all directions. When masses of fine and coarse granular materials such as the mineral aggregates used in bituminous pavements or in granular bases (or even in the underlying basement soils) are combined with varying amounts of water or of asphalt or both, all such materials form combinations that will transmit some pressure in all directions but not in a

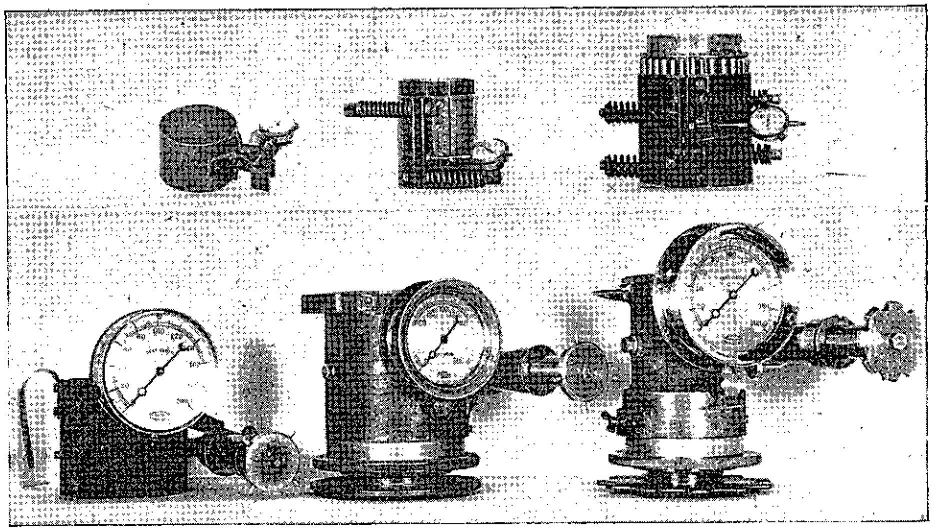


FIG. 7.—Showing the Evolution of the Stabilometer Through a Series of Types of Models.

uniform pattern or to an equal degree. Therefore, if a sample of a typical bituminous pavement or of granular base material is placed in a cylinder and subjected to a load under a tight fitting piston, a certain percentage of the vertical pressure will be transmitted to the side walls of the cylinder. The proportion of the vertical pressure thus transmitted in a lateral direction may vary considerably however, depending upon the character of the sand or rock particles and especially with the amount or type of lubricating liquid that is combined. The whole relationship and condition may be summarized by stating that the lateral pressure will vary inversely with the internal resistance of the mass. This internal resistance of bituminous paving mixtures has usually been referred to as "stability." If a specimen of soil or mineral aggregate with or without a bituminous binder is compacted in the form of a cylinder and subjected to vertical loading with means for measuring the lateral pressure developed in the process, then the relative tendency of the material to transmit lateral pressure will present an index to the stability or "resistance value" of the material in place on the roadbed.

As illustrated by Fig. 7, the Stabilometer has evolved through a series of types or models to its present form.

The Stabilometer test was first described in a paper published in the *Proceedings* of the Highway Research Board in 1934.[11] Further discussion was included in an article published by the American Road Builders' Association in 1939.[12]

As indicated in the earlier reports, the design of the instrument is such that it is possible to test specimens artificially compacted in the laboratory or those cut from the pavement by means of a core drill. This latter feature has made it possible to establish a direct comparison between test results on artificially formed specimens and those fabricated by the usual construction methods involving rolling and traffic compaction. As soon as such comparisons were established, it became clearly evident that laboratory compaction methods involving tamping under a hammer developing sharp impact followed by direct confined compression loading, consistently produced test specimens that were unlike the actual road surface, being far more stable than were samples cut from the pavements composed of the same ingredients. This was true even though the tamped specimens *developed the same density as the field cores*. Therefore, a lengthy study was undertaken in order to establish a

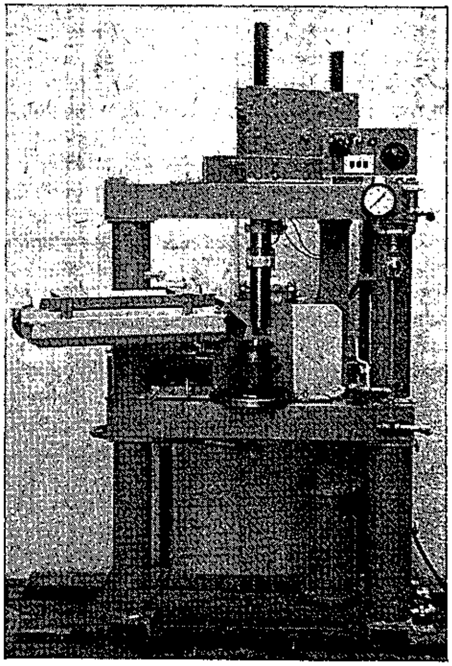


FIG. 8.—Mechanical Compactor (Model B) Constructed by California Division of Highways in 1950.

laboratory compaction technique that would reproduce in all respects the resistance properties of the mixture when compacted on the roadway (Fig. 8). The development of the compaction procedure has been discussed in this paper and elsewhere.[10]

Having provided means for preparing a test specimen in which the compaction pressures, arrangements of particles, density and *film thickness of asphalt* are all fairly typical of actual pavement conditions, the next step is the conduct of the test.

[11] T. E. Stanton, Jr., and F. N. Hveem, "Role of the Laboratory in the Preliminary Investigation and Control of Materials for Low Cost Bituminous Pavements," *Proceedings*, Highway Research Board, Vol. 14, Part II, December, 1934, pp. 15–54.

[12] F. N. Hveem, "Use of Stabilometer Data in the Design of Flexible Road Surfaces," *Proceedings*, American Road Builders' Association, March, 1939, pp. 167–172.

The Stabilometer test is accomplished by placing the compacted test specimen within the Stabilometer shell where it is supported upon the base column and surrounded by the closely fitting rubber tubing. A series of photographs are included in Fig. 9 illustrating the sequence of operations involved. The total lapsed time to perform the test ranges from five to six minutes. With the test specimen in place and the follower or loading piston resting on the upper surface of the test specimen, the Stabilometer is placed on the platen of a testing press and the specimen subjected to a load applied at the rate of 0.05 in. per min. Continuous readings of the Stabilometer dial are recorded; typically at each 1000 lb. of

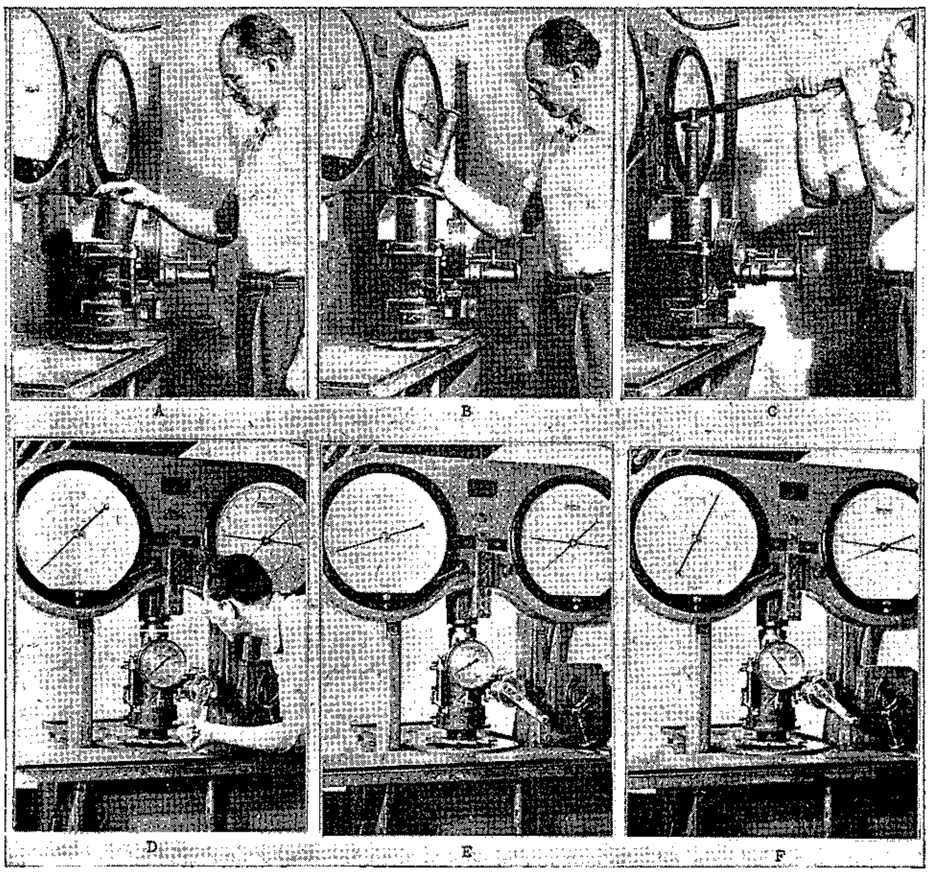


FIG. 9.—Showing Sequence of Operations Involved in the Stabilometer Test.

A—Steel mold 4 in. in diameter containing compacted test specimen is placed in position on top of Stabilometer. Mold fits into recessed seat providing correct alignment.

B—Steel follower or ram with 4 in. diameter face is placed on surface of test specimen inside of steel cylinder.

C—The specimen is forced into position in Stabilometer by means of a hand lever engaging a fulcrum on testing press.

D—Steel mold is removed, loading follower is put in place and Stabilometer is placed on the platen of the testing press. The operator is shown adjusting the initial lateral pressure to 5 psi. by means of the displacement pump.

E—Test under way. The left-hand dial of the testing press indicates 1000 lb. total load which corresponds to approximately 80 psi. (P_v) on a specimen having an end area of approximately 12.5 square inches. On the specimen shown, the Stabilometer dial indicates about twelve pounds lateral pressure (P_h) at this point.

F—The testing press is operated at a speed of 0.05 in. per min. and loading is continued at this rate until a total of 6000 lb is reached (480 psi.), (at which point the specimen shown registers a lateral pressure of approximately 87 psi.) For bituminous surfaces, "stability" is calculated from the Stabilometer readings taken when the vertical load is equal to 400 psi.

total load. For comparative purposes "stability" is reported under a total load of 5000 lb. which is equivalent to approximately 400 psi. on a specimen 4 in. in diameter. The test is not carried out to reach any yield point or "failure" point.

The process of testing a sample of road material in the Stabilometer is based on the premise that a sample should be subjected to pressures sufficient to represent the combined effects of traffic loads frequently repeated

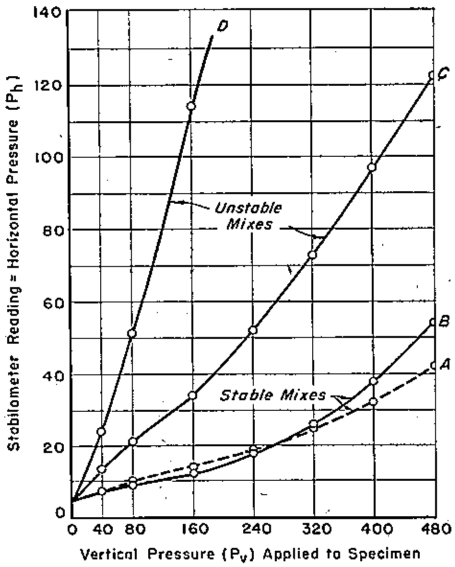


FIG. 10.—Chart Showing Stabilometer Reading (P_h) Under Different Vertical Loads (P_v).

over a long period of time. Under the conditions of the test, a load ranging from 300 to 400 psi. seems to furnish a reasonable duplication of the cumulative long time effects from pneumatic tired traffic. Therefore, the sample is subjected to a slowly applied load culminating in a pressure of 400 psi. and the Stabilometer reading under each 1000 lb. of total load is recorded. After reaching the maximum load, the "displacement value" of the Stabilometer system is measured and recorded. This displacement value represents the volume of liquid expressed in cubic inches (or in the number of "turns" or revolutions of the calibrated pump handle) required to increase the pressure in the apparatus from 5 to 100 psi. This measurement is made with the specimen in place and any compressible components contributed by the specimen will be reflected in the displacement measurement. It has been found that the magnitude of the lateral expansion or the volume displaced by the specimen while undergoing the test must be taken into account when evaluating the lateral pressure developed. In other words, two test specimens of the same asphaltic mixture will give different lateral pressures depending upon the range of movement permitted to the specimen and this range or volumetric expansion is evaluated on each specimen by the displacement measurement. Therefore, the displacement is measured after the completion of the test by turning the displacement pump handle in a clockwise direction, thus forcing a volume of liquid into the Stabilometer sufficient to develop a pressure of 100 psi. The exact amount of liquid required is indicated by the number of turns of the pump and may be read on the Ames dial gage provided.

In the conduct of this test, the specimen becomes in effect an integral part of the Stabilometer system and therefore, any lateral surface voids on the specimen or air entrained in the Stabilometer liquid will influence the lateral displacement required to develop a given pressure.

As specimens differ in the degree of smoothness or roughness of the exterior surface, it is necessary to measure the actual displacement for each test. The specimen is held firmly in place during the displacement measurement by retaining a vertical pressure of about 1000 lb. This is employed simply to prevent the test specimen from being deformed or squeezed upward while the displacement measurement is being carried out. Early studies indicated that the significance of test results was impaired when the total displacement in the instrument was at a very low value. Under such conditions, it was difficult to establish a differential between specimens of high and low stability. Therefore, a standard initial displacement was adopted corresponding to two turns of the hand pump when a "dummy" specimen such as a smooth cylinder of brass or wood is in place. All compacted specimens of bituminous materials give a displacement value somewhat higher than is recorded for the smooth unyielding dummy specimen. To repeat; it is necessary that the conditions of compressibility within the entire Stabilometer system must be evaluated for each specimen. While in a sense the displacement value is a correction for the test specimen itself, fundamentally it is a correction for the entire Stabilometer system as air voids anywhere in the system will have the same effect on the instrument reading.

The foregoing discussion and test procedure imply that the tendency of the specimen to transmit vertical pressures in a horizontal direction is an inverse measure of the ability of the specimen to resist deformation. Following the idea that plastic materials form a class of substances intermediate between liquids and rigid solids, an arbitrary scale for reporting stability was established many years ago in which the value of zero corresponds to a liquid having no measurable internal resistance to slowly applied loads and at the other extreme, 100 corresponds to a hypothetical solid that will transmit no measurable amount of pressure or movement.

Calculating Relative Stability:

For many years, Stabilometer values have been converted to this arbitrary stability scale by the following empirical formula:

$$\text{Relative Stability} = S = \frac{22.2}{\dfrac{P_h D_2}{P_v - P_h} + 0.222} \quad \ldots (1)$$

where:

P_v = vertical pressure (typically 400 psi.),
P_h = horizontal pressure (Stabilometer reading in psi.), and
D_2 = displacement on specimen.
(P_h was taken at the instant P_v was 400 psi.)

It will be noted that three factors are involved in determining the relative stability; first, the test load or vertical pressure (P_v); second, the horizontal pressure (P_h) developed as indicated by the Stabilometer reading; third, the volume of liquid which must be displaced (D_2) to change the pressure on the Stabilometer dial from five pounds to one hundred pounds. For a bituminous paving mixture having a small amount of cohesion or tensile strength such as would ordinarily be obtained with an SC-2 or SC-3 liquid asphalt, a value of S equal to or greater than 35 would be considered satisfactory. However, it is evident that mixtures containing asphalts of low penetration have characteristics of hardness or toughness quite different from the oil mix

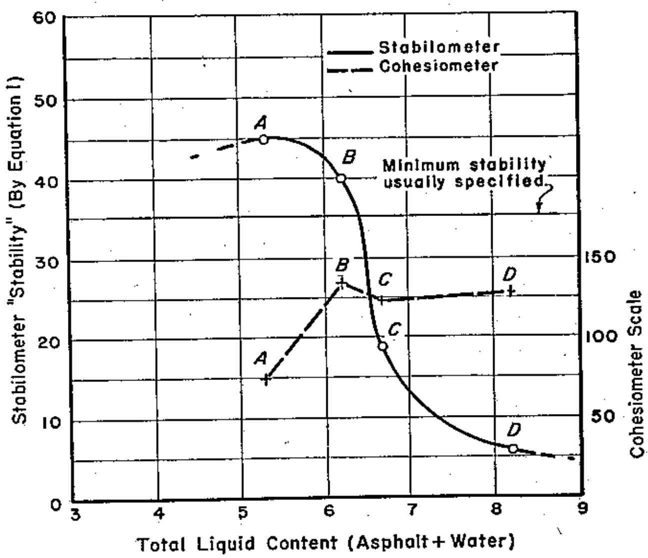


FIG. 11.—Stabilometer and Cohesiometer Values on Four Specimens With Different Liquid Content.

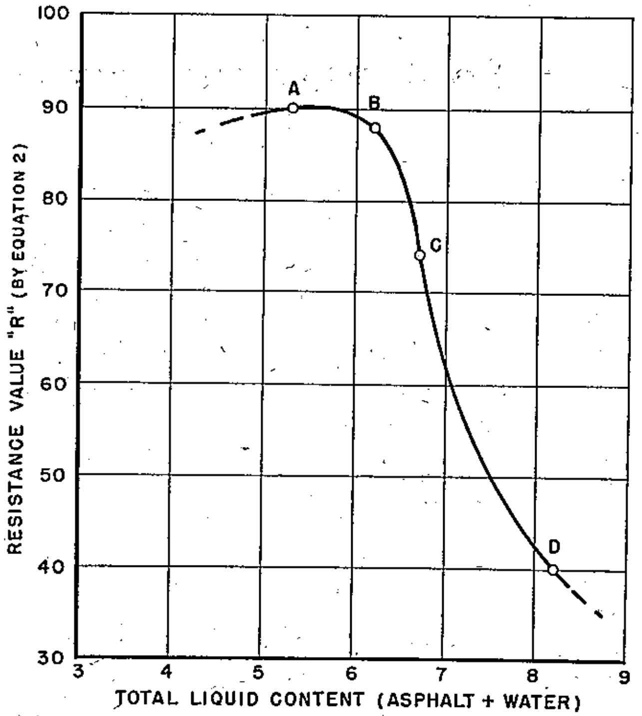


FIG. 12.—Resistance Value Calculated From Stabilometer Results Alone.

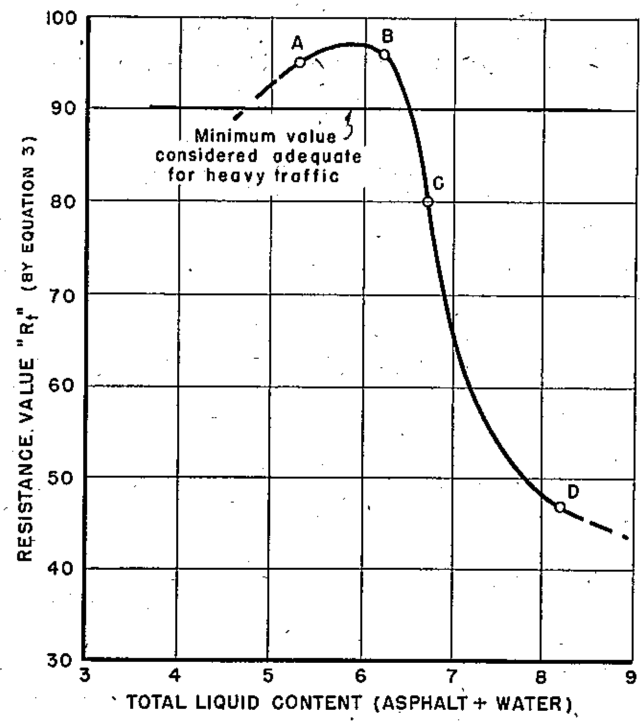


FIG. 13.—Resistance Value Calculated to Include Both Stabilometer and Cohesiometer Values.

type. In order to evaluate this property, the cohesiometer[11] was developed to measure the cohesive strength of the asphalt films. This is accomplished by bending or breaking the same cylindrical test specimen as used in the Stabilometer. The cohesiometer test is comparable to a cantilever beam test and cohesiometer values have a linear relationship to modulus of rupture values when applied to rigid or non ductile substances.

Within recent years, Stabilometer tests are being applied to native soils and granular bases in order to evaluate the supporting power and thus determine the thickness of pavement or surfacing required. The ability of such materials to resist distortion has been designated "the resistance value" and while the two extremes of zero or 100 also correspond to the liquid and solid state respectively, the intermediate values have a different order of correspondence as compared to the older "stability" scale.

When calculating the resistance values of soils or untreated granular bases, the following formula is used:

$$R = 100 - \frac{100}{\frac{2.5}{D_2}\left(\frac{P_v}{P_h} - 1\right) + 1} \quad \ldots (2)$$

where R is the resistance value.

The other symbols have the same significance as in Eq. 1. However, P_h will be taken when P_v is at 160 psi. The R value may be used to compute the thickness and strength of pavement necessary to carry traffic loads.[10]

Both of the foregoing equations neglect the cohesion or tensile strength of the soil or bituminous surface but under certain conditions it is desirable to have an over-all evaluation in which the tensile strength is included.

For bituminous surfacings, we are now calculating a total resistance value combining both friction and tensile strength as reflected by Stabilometer and cohesiometer readings.[11] The formula is as follows:

$$R_t = 100 - \frac{100}{\frac{2.5}{D_2}\left(\frac{P_v}{P_h} - 1\right) + 1} + 0.05\, c_1 \quad \ldots (3)$$

where R_t is the total resistance value due to both friction and cohesion and c_1 is cohesiometer value in grams per lineal inch of specimen width. This is an index to the tensile strength of the specimen.

When calculated by the above formula, a value of R_t equal to or greater than 90 is sufficient and generally necessary for a bituminous pavement subjected to heavy pneumatic tired traffic.

Since the development of the Stabilometer, instruments embodying the same principles have been constructed in many laboratories, many of which have been designated as "apparatus for measuring triaxial shear." So far as fundamental principles of the apparatus are concerned there is no difference between the Stabilometer and the "triaxial versions." However, there has been a rather general and consistent difference in the theoretical approach or concept and consequently in the methods of conducting the test. As stated before, the Stabilometer is employed to measure the ability of the compacted specimen to transmit pressure and the entire range of plastic materials may be evaluated by this process. Sands or similar cohesionless granular materials may also be tested in the Stabilometer without difficulty. In most conventional triaxial tests, however, the test is conducted on the assumption that there is a definite point of "failure" and a typical procedure is to apply a series of lateral pressures or degrees of lateral support to the specimen and then determine the vertical load required to cause "failure" in the specimen. The specimen is subjected to several stages or steps in magnitude of load and of lateral support.

In order to illustrate the application of the stabilometer test, four samples of bituminous mixtures were selected and the test data are shown on four charts (Figs. 10, 11, 12, 13). The four samples were submitted from a recently constructed project with the request that the laboratory determine the causes for distortion and roughening of the pavement represented by samples C and D. Samples A and B were taken from stable sections.

These samples are identified and the test results tabulated in Table I.

Examples of Test Results on Stable and Unstable Materials:

Figure 10 has been prepared showing the Stabilometer readings recorded for these four samples. This is accomplished by plotting the

Stabilometer reading in pounds per square inch against the applied load in pounds per square inch. Under the conditions of the test, the vertical and horizontal pressures will be identical on a specimen having no internal friction or resistance. (The relative stability for bituminous pavements is evaluated under a test load of 400 psi.)

Chart, Fig. 11, shows the "stability" value calculated by means of Eq. 1. The cohesiometer values have also been superimposed indicating that cohesiometer values or tensile strengths tend to increase with an increase in the liquid content, which is a typical trend in the majority of cases. Based on Stabilometer tests, specimens A or B would be considered to be satisfactory, however, it will be by the higher asphalt content undoubtedly would account for the comment from the field engineer that specimen B was "Best looking mix to date." However, the asphalt content in this specimen is dangerously close to the upper limit for stability and slight errors in plant proportioning or in the introduction of an excessive amount of moisture would render all or portions of the mix unstable as indicated by the steep decline in the curve.

It must be emphasized that the four specimens tested are not of identical composition as they were taken from different points on the roadbed and as will be seen in Table I, there is some variation in the percentage of fines which probably contributes to the low Stabilometer value on specimen D.

TABLE I.—TEST RESULTS ON SAMPLES OF BITUMINOUS PAVEMENT REPRESENTING BOTH STABLE AND UNSTABLE AREAS ON THE SAME PROJECT.

Test	Identification letter used on Charts and in following discussion	Percentage Passing No. 200 Sieve	Percentage of Moisture in Material	Percentage of Asphalt by Extraction	Cohesiometer Value at 140 deg.	Stabilometer Value[a]	Comments on Condition of Road
No. 57649	A	10	1.0	4.3	74	45	Condition good. No sign of failure.
No. 57650	D	15	2.7	5.5	129	6	Condition poor. Bumps bladed off.
No. 57651	C	10	1.2	5.5	124	19	Condition poor. Bumps bladed off.
No. 57652	B	9	1.1	5.1	135	40	Condition very good. Best looking mix to date.

[a] Stabilometer tests were made on the samples as received without drying.

noted that the stability falls very rapidly with a slight increase in asphalt or water content beyond the amount found in specimen B. Therefore, it has been considered good practice to specify a somewhat lower asphalt content in order to provide some latitude for variation during construction.

Chart, Fig. 12, has been prepared to show the corresponding resistance value calculated from Eq. 2. Either the R value or the stability value places the four specimens in about the same relative order. However, the tensile strength is also a factor in the performance of a bituminous pavement and Chart, Fig. 13, has been prepared to show the resistance value calculated according to Eq. 3 which represents the combined influence of internal friction and tensile strength. Under this evaluation, specimen B appears slightly superior and the additional toughness imparted

It should also be noted that there is no difference in asphalt content between specimens C and D. The chief distinction is in the fact that specimen D contains about twice as much moisture as specimen C.

The test results on the above samples were selected because the actual quality of the materials could be attested by known performance under traffic. The four samples also serve to illustrate the variations caused by differences in asphalt content and the similar influence of varying amounts of moisture.

Summary:

It may be stated that the Stabilometer is an instrument capable of measuring the most important elements of internal resistance in a wide variety of granular or plastic materials with or without bituminous binders ranging from cohesionless sands to wet clays and will

also produce significant values on test specimens of soil cement mixtures.

The entire test procedure can be completed within an elapsed time of six minutes and the test specimen is not ruptured or destroyed in the process so that the same briquet may be used to determine the tensile strength or cohesive resistance if desired.

The first and outstanding advantage of the Stabilometer is the speed with which tests may be performed. This is a matter of paramount importance in any laboratory where cost of testing is a consideration and where test results must be made available as soon as possible for job control purposes.

The second feature is the fact that the test has been in use for more than fifteen years and a large mass of data exists to demonstrate that a high degree of correlation exists between test results and known performance of soils, base materials and bituminous surfaces under motor vehicle traffic.